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The structure of the October/November 2005 outburst in OJ287 and the precessing binary black hole model *(Research Note)*

M. Valtonen[1,2], M. Kidger[3,4], H. Lehto[1,5], and G. Poyner[6]

[1] Department of Physics and Tuorla Observatory, University of Turku, Turku, Finland
e-mail: `mvaltonen2001@yahoo.com`
[2] Department of Physics, The University of The West Indies, St. Augustine, Trinidad and Tobago
[3] Herschel Science Centre, European Space Astronomy Centre, Villafranca del Castillo Satellite Tracking Station, Apartado 50727, Madrid, Spain
[4] INSA
[5] NORDITA, Blegdamsvej 17, Copenhagen, Denmark
[6] British Astronomical Association Variable Star Section

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ABSTRACT

Aims. The blazar OJ 287 had its biggest optical outburst in over 20 years. It occurred in October/November 2005 and was somewhat expected since similar outbursts had occurred at approximately 12 yr intervals since the early 1900s. However, a strict periodicity would have put the event nearly a year later. Here we ask whether the October/November 2005 outburst was indeed the expected 2006 outburst of OJ287. Did it follow the typical light curve behaviour of such events: a rapid initial rise in just over a week and a slower decay in the following months?
Methods. In this study we use the extensive observations of The British Astronomical Association Variable Star Section, complemented by the data from The American Association of Variable Star Observers. We compare the 2005 outburst with the previous season's first peak of 1983.
Results. We find that the beginning of the 2005 outburst occurred at 2005.76, a few weeks earlier than was reported previously. The timing of the outburst is consistent with the binary black hole model of Lehto and Valtonen. In accordance with this model, we find that the outburst's structural time scale is slower in 2005 than in 1983, while the 2005 outburst was fainter than the 1983 outburst, making the two outbursts about equal in energy. Thus it is quite reasonable to argue that the 2005 outburst was the expected first of the season in the optical light curve of OJ287.

Key words. galaxies: quasars: individual: OJ287

1. Introduction

The blazar OJ287 has had major outbursts at approximately 12-year intervals (Sillanpää et al. 1988, 1996). The next outburst was widely expected in 2006 (Lehto & Valtonen 1996; Kidger 2000). Surprisingly, OJ287 showed its biggest outburst over twenty years as early as October/November 2005 (Valtonen et al. 2006a). The question addressed in this paper is whether this outburst qualifies as one of the regular series observed since 1913.

The timing of the 2005 outburst is consistent with the precessing binary black hole model (Lehto & Valtonen 1996; Sundelius et al. 1996, 1997; Valtonen 2007). The model starts from an exact solution of the orbit, based on the idea that optical flashes are generated at a constant phase angle of the secondary orbit. The constant phase angle may arise from the secondary crossing the accretion disk of the primary (Ivanov et al. 1998). Knowledge of the exact timing of six flashes is enough initial data to provide a unique orbit solution. Before the 2005 event, only four well-timed outbursts were known, making the orbit solution and its predictions quite preliminary. For this reason it is important to obtain a good relative timing between the 2005 outburst and the 1983 outburst. The earlier date is usually kept as a standard reference time, 1983.00 being the starting time of the outburst.

The precessing binary black hole model also makes predictions with regard to the outburst time scale which can now be checked for the first time. We expect that the 2005 outburst was about seven times as slow as the 1983 outburst. The decay of flux in the 2005 outburst should follow a $-3/2$ power law with scale length of 0.205 yr (Lehto & Valtonen 1996).

We present the observations of the 2005 outburst and the light curve up to the summer 2006 conjunction. These are used in a comparative study of the 2005 and 1983 outburst light curves to determine the relative timing between the two events. We then compare the general forms of the light curves of the 1983 and 2005 outbursts.

2. Observations of OJ287 in 2005/06

The British Astronomical Association Variable Star Section (BAA-VSS) has had OJ287 in its list of targets since 1993. An observing campaign was launched in 2005 in anticipation of a new outburst following the approximately 12-year cycle in the

Table 1. Number of observations in the archive of the BAA-VSS used in this paper.

	Visual	Unfiltered	*B*	*V*	*R*	*I*
BAA	120	186	29	55	25	8
AAVSO	5			31		

light curve, with the aim of detecting and defining it once the outburst occurred. A total of 423 mag were reported by participating observers between January 10 2005 and June 11, 2006. The reason for including the data only since the start of 2005 is that, prior to this date, 287 of the 311 (92%) magnitudes in the archive were visual estimates. In contrast, during the campaign described here, 318 of 438 (73%) of the reported magnitudes are from CCD photometry: either unfiltered and reduced as pseudo-*V* (63% of reported CCD magnitudes) or made with standard *BVRI* filters (37%). Details of the distribution of observations by method and/or filter are given in Table 1. The columns show the number of visual magnitude estimates, unfiltered CCD photometry and filtered photometry in *B*, *V*, *R* and *I* bands, respectively. A few observations during the rise of OJ 287 in September were adopted from the AAVSO archives. Table 2 lists further details showing the contributing observers, IAU Minor Planet site code or location of the observatory, the size of the instruments and the type and number of observations reported.

Photometry was reduced using the standard BAA-VSS sequence (Toone 2006). At the faint end ($V > 13.5$), this is based on the photometry of field stars by Gonzalez-Pérez et al. (2001), and Kidger et al. (2004), and at the bright end on CCD measures from Miles (private communication) and Smith et al. (1985). We note that Star 4 of the standard sequence (Penston & Wing 1973), often found to be discrepant in previous calibrations of the field, has been eliminated, as monitoring at Teide Observatory over the period from 1993–2002 has shown that it is clearly variable with an amplitude slightly greater than 5%.

On examining the photometry taken in different systems (visual, unfiltered CCD, and CCD+V), it was evident that there were small but systematic offsets in the data. An empirical correction was determined by comparing data in each system that was taken within an hour of each other, assuming that in most cases there would not be a signification variation of OJ287 on this time scale. This is effectively a first-order colour correction to standard *V* magnitude: visual +0.14 and unfiltered +0.09. These corrections should be added to the magnitude to give standard *V*. In both cases this first-order colour correction makes the corrected magnitude significantly fainter. When the corrections are included, there is excellent agreement between data obtained in the three photometric systems.

We find that the mean colour indices for OJ287 during the observing campaign are $(B-V) = +0.62$, $(V-R) = 0.44$, $(V-I) = +1.04$, with no significant evidence of colour variations over the period covered here, thus a first-order colour correction is valid. When the data were corrected, the agreement between different systems was excellent, as shown in Fig. 1 where the observations from the first six months of 2006 are presented on an expanded scale. *B*, *R*, and *I* data were used to confirm the constantness of the colour indexes.

Our data was somewhat sparse during the middle of 2005, so we have added data points from the American Association of Variable Star Observers (AAVSO) light curve to this section.

The full light curve from the start of 2005 is shown in Fig. 2. A maximum at $V = 13.6$ is seen at 2006 November 7 ± 2 days, while the magnitude was $V = 14.8$ in early October and below 15 in May 2005. Examination of the BAA-VSS archive shows that OJ287 had been brightening slowly, but persistently, since early 2003 and that in November 2005 it was brighter than at any time since 1985.

After maximum, the magnitude faded to $V \sim 16$ by mid-June, although there was also brief deep minimum to $V = 16.1$ in mid-February that lasted for 9 days at half minimum. There was some flaring activity during the decline from the outburst, e.g. a well-defined flare of 1 mag amplitude in early April and a smaller flare in late December–early January.

3. Light curve comparison

In Figs. 3 and 4 we compare the 1983 and 2005 outburst light curves with the standard theoretical outburst light curve in mJy units. A comparison of the peak brightness of the 1983 outburst (31 mJy) with the peak brightness in 2005 (13 mJy) shows that the 1983 outburst rises about a factor of two higher above the base level (base level around 6 mJy) than the 2005 outburst (base level around 1.25 mJy), as determined from the level outside the outburst. It is also immediately apparent that the 2005 outburst lasted much longer than the 1983 outburst. Thus the total integrated energy of the 2005 outburst is at least equal to the energy of the 1983 outburst, a statement which is independent of any theoretical models and which is easily verified by integrating the outburst energies from the corresponding light curves.

From the point of view of the binary black hole model, one interesting question is the exact time of the beginning of the 2005 outburst in relation to the 1983 outburst. The previous fixed points in the orbit solution of the binary orbit are the 1947, 1973, 1984, and 1994 flares, which have been tied to the 1983.00 system by cross-correlation analysis (Valtonen et al. 1996). Here we do the same for the 2005 flare so that it can be used similarly in orbit solutions. However, a cross-correlation study is not the best method in this case since we expect the outburst time scales to differ by a factor of about seven, the 2005 outburst being slower by this factor than the 1983 outburst (Lehto & Valtonen 1996). Thus we tested the theory directly by plotting the 2005 observations as weekly averages (Fig. 4) and all the available 1983 observations (Fig. 3), and compared both with the theoretical light curve.

The first point to notice about these figures is that there is a good match between the observations and the theory. Thus the relative timing must be such that the reference time at 2005 is 2005.76 in the usual system where the reference time in 1983 is taken as 1983.00. This is different from earlier determinations by about 3 weeks (Valtonen et al. 2006a).

The second point is that the outburst area under the 2005 light curve is at least equal to the area under the 1983 light curve. It means that the 2005 outburst may have been even more powerful than the 1983 outburts.

The third point is evident from the superposed lines. The line for the ascending part is linear, corresponding to the light travel time through the radiating bubble, while the descending part follows a $-3/2$ power law, as expected in the model. The time during which the flux falls by a factor of 2 is called the outburst time $t_{\rm outb}$; in the model it was calculated as 0.018 yr in 1983 and 0.129 yr in 2005 (Lehto & Valtonen 1996). As seen in Figs. 3 and 4, the lines drawn using this model are fairly close to what was observed. The flaring on top of the model light

Table 2. Contributing observers and number of observations since January 1, 2005.

Observer's name	IAU MPC site code or location	Telescope diameter	*N* visual	*N* unfiltered CCD	*N* filtered CCD
G. Poyner	Birmingham, UK	35 cm	44		
J. Shears	Bunbury, UK	10 cm		40	
M. Mobberley	Cockfield, UK	35 cm		1	
J. Toone	Cressage, UK	35 cm	41		
R. Leadbeater	Cumbria, UK	20 cm		5	10
J. Virtanen	Finland	50 cm	6		
S. Karge	Frankfurt, Germany	28 cm	19	8	
S. Brady	Hudson, USA	25 cm			13
M. Simonsen	Imlay City, USA	30 cm			
D. Storey	Isle of Man, UK	40 cm	2	4	
T. Haynes	Knowl Hill, UK	20 cm		7	
A. Jones	Maidenhead, UK	25 cm		14	
C. Meredith	Manchester, UK	20 cm		8	
R. Naves and M. Campás	MPC 213	30 cm		5	
A. Sánchez	MPC 442	35 cm		3	
D. Rodríguez	MPC 458	20 cm		2	4
F. Ocaña, A. Sánchez-de Miguel, B. Pila and I. Guirado	MPC 493	150 cm			1
Bradford Robotic And Telescope (G. Poyner)	MPC 954	35 cm		18	
E. Cortès and F. Garcia	MPC A06	25 cm		5	
J. Barceló, F. Morillas, C. Rodríguez and M. Casao	MPC A10	30 cm		1	
R. Miles	MPC J77	28 cm		4	5
F. Melillo	New York, USA	20 cm		15	
T. Crawford	Oregon, USA	30 cm			47
J. McCormick	Pakuranga, NZ	25 cm		34	
R. Pickard	Shobdon, UK	30 cm		11	5
T. L. Evans	St. Andrews, UK	35 cm	9		
R. Patterson	Thame, UK	25 cm	2		
A. Wilson	Tonbridge, UK	25 cm		5	
G. Salmon	Truro, UK	25 cm			3
D. Boyd	Wantage, UK	35 cm			20
C. Jones	West Hanningfield, UK	45 cm	7		

curve could be assigned to the usual short time-scale brightness fluctuations in OJ287 and may not have any further significance. The model is based on Bremsstrahlung opacity; but in fact, electrons are accelerated to high energies in the strong shocks (Mach 6–7) when the secondary black hole impacts on the accretion disk of the primary. While it is very difficult to be quantitative about the synchrotron emissivity in this process (which is why the Bremsstrahlung model was used in the first place), the qualitative behaviour of the outburst should be the same.

The situation may be clarified by polarization studies: the appearance of a Bremsstrahlung component should always reduce the degree of polarization at the outburst, while the superposition of a new synchrotron component on top of an existing one may either raise or lower the degree of polarization at the outburst, depending on the relative position angles of polarization of the components.

Note that the process through which the OJ287 orbit model has evolved is typical of orbit determinations in general, e.g. of minor planets. Initially only the minimum number of observations (as few as three observations) are used to obtain a tentative orbit. It is hardly expected to be the final orbit solution, but it helps in planning further observations until rather definite orbit parameters have been determined. In the case of the OJ287 binary orbit, we have just moved, with the timing of the 2005 flare at 2005.76, from the first tentative to the second tentative orbit. At least one more flare, in September 2007, is required for the definite orbit parameters.

We limit our discussion to this model only, because it is unclear at this time if any of the competing models can explain the

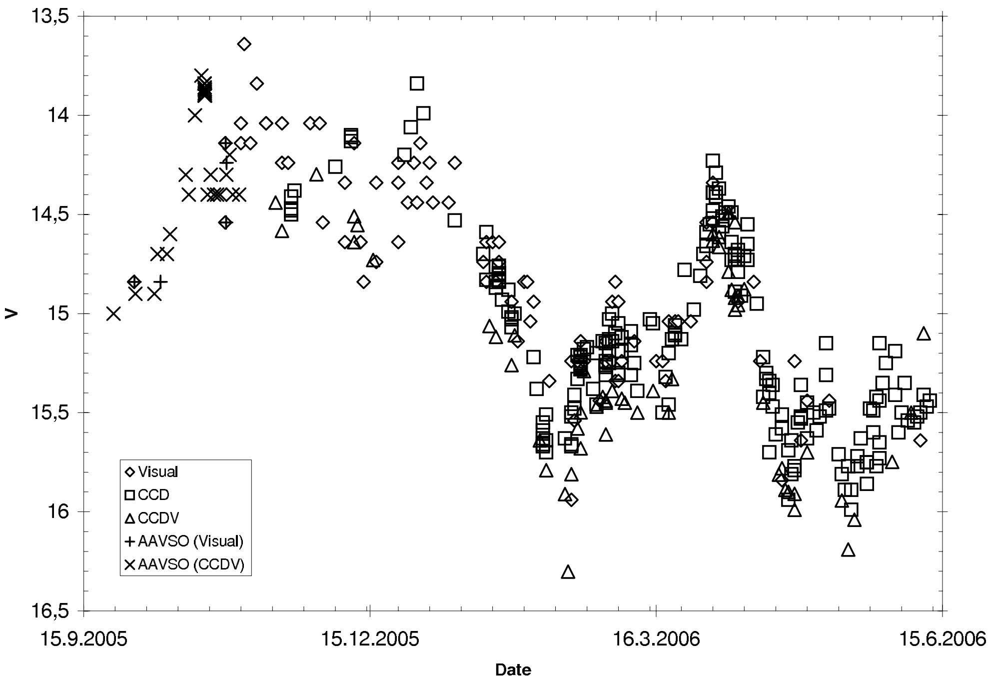

Fig. 1. The data for the first six months of 2006 on an expanded scale showing the excellent agreement between the data obtained using the three different photometric systems.

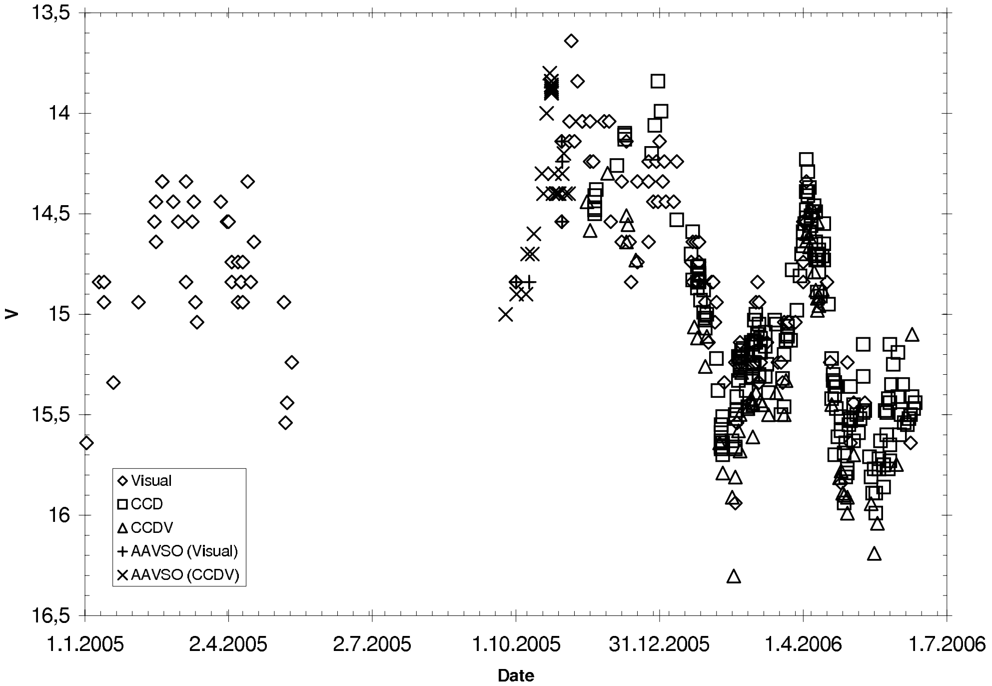

Fig. 2. The full light curve from the data obtained in 2005/2006.

outburst as early as October/November 2005. See Valtaoja et al. (2000) and Valtonen et al. (2006b) for a discussion of different models.

4. Discussion

One of the predictions of the Lehto & Valtonen (1996) model is that the time scales of the outbursts should be longer the further the impact takes place from the primary. Here, the 2005 outburst should be slower than the 1983 outburst by about a factor of seven (Lehto & Valtonen 1996). Our Figs. 3 and 4 demonstrate that this expectation has been met and also that the 2005 outburst may have been energetically stronger than the 1983 outburst. The latter is the biggest well-documented outburst of its kind in OJ287, and since the 2005 outburst may have been even greater, there is every reason to identify the 2005 outburst as the expected 2006 outburst.

This conclusion is enforced by the fact that, disregarding some small-scale fluctuations, the outburst profiles both in 1983 and in 2005 follow the theoretically calculated outburst profile in OJ287 rather closely. This is a further argument in favour of the precessing binary black hole model. The beginning of the outburst, found here to be at 2005.76, is also consistent with the model. It is a little earlier than in the latest orbit solution (2005.82 in Valtonen 2007), but the new timing can be accommodated e.g. by changing the eccentricity of the binary orbit

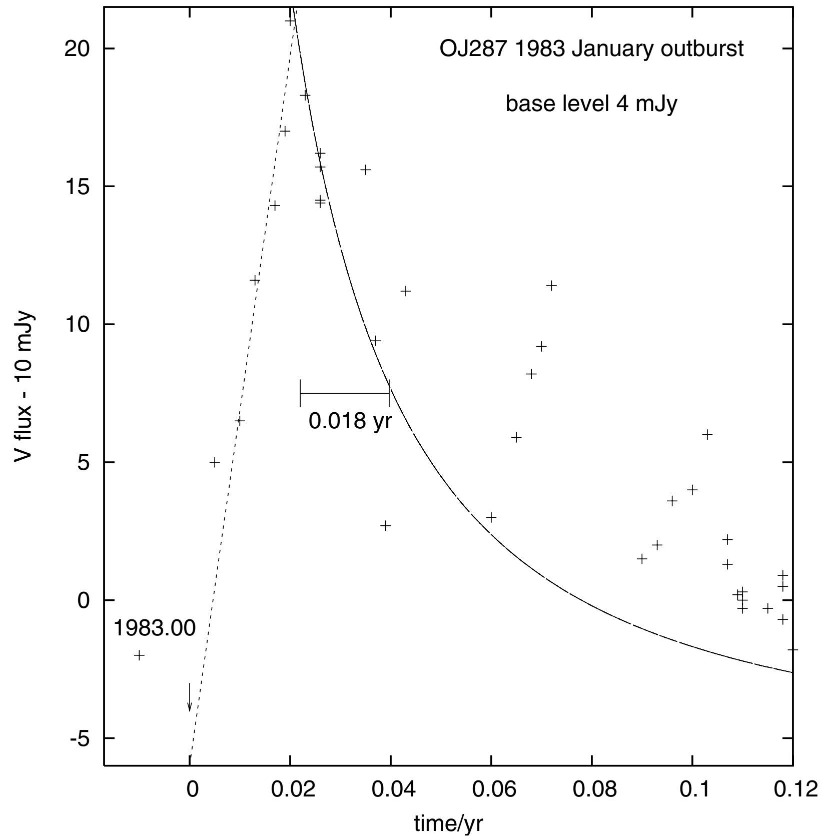

Fig. 3. Light curve at 1983 on a linear scale together with theoretical lines. Flaring is observed above the theoretical outburst level.

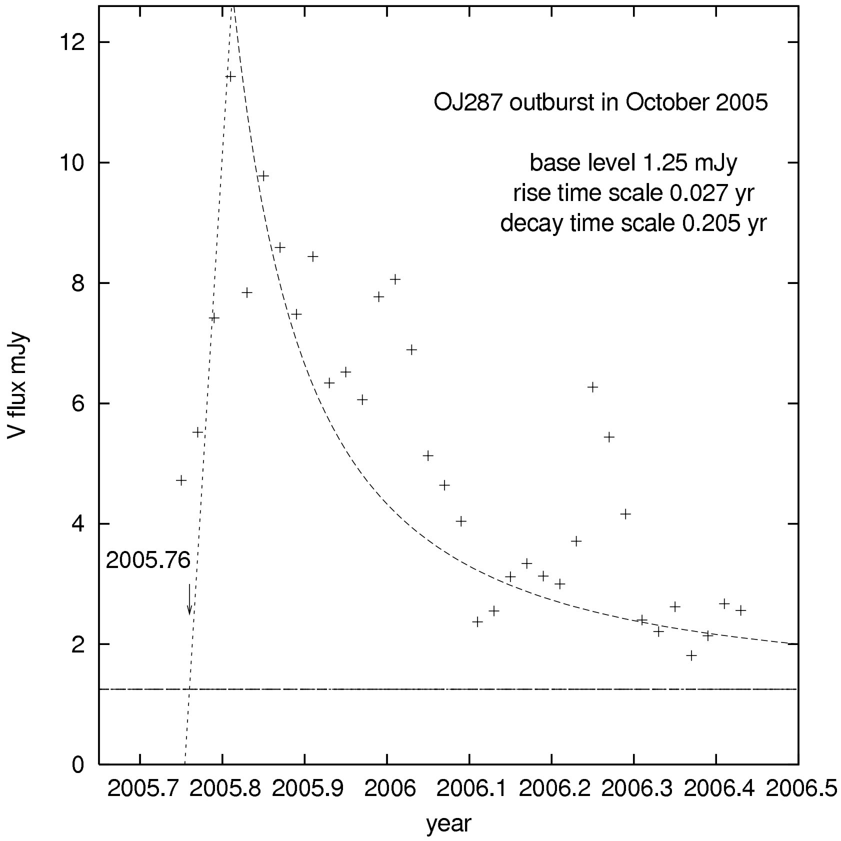

Fig. 4. 2005 outburst light curve compared with theory in linear scale. The rising part is taken as linear while the decay is adiabatic and follows a power law of index –3/2.

from 0.661 to 0.663 in the case that the precession is 39 degrees per period. However, until another fixed point is obtained from observations, it is not worthwhile computing more accurate orbit solutions.

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